Implications of Vector Boson Scattering Unitarity in Composite Higgs Models

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Introduction

- Despite its incredible success, the SM is plagued by several problems.
- Composite Higgs (CH) models are among the most promising alternatives,
- dynamically generating the EW scale through a vacuum condensate misaligned with the vacuum that breaks EW symmetry

$$v = f \sin\theta$$

- and at the same time explaining the mass gap between the Higgs and the other composite states $\rightarrow$ Higgs = Goldstone boson of spontaneous symmetry G/H.

- A striking evidence of strong dynamics is the growing (with E^2) behavior of **Goldstone Boson Scattering (GBS)** amplitudes

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{f^2} = \frac{s}{v^2} \sin^2\theta \,,$$

- controlled by strong effects at high energies, broad continuum or composite resonances, saturating unitarity - similar to hadron physics.
- Perturbative unitarity is a powerful tool to assess the scale of strong effects and properties of the composite spectrum.

Effective Lagrangian

- The **(pseudo-)Goldstone bosons** can be described by the CCWZ construction, at $d = 2$,

$$\mathcal{L}_2 = \frac{1}{2} f^2 \langle x_\mu x^\mu \rangle$$

- Higgs coupling hVV deviation (mainly) $\sim \cos\theta$ disturbs EWPO

$$\sin\theta \lesssim 0.2 \quad \text{(EWPO)}$$

- Different origins of vacuum alignment in effective potential typically implies not so small θ (model dependent)
- To analyze perturbative unitarity it is imperative to include higher order terms $\rightarrow$ together with high dimensional operators. At $d = 4$,

$$\begin{aligned} \mathcal{L}_4 &= L_0 \langle x^\mu x^\nu x_\mu x_\nu \rangle + L_1 \langle x^\mu x_\mu \rangle \langle x^\nu x_\nu \rangle \\ &+ L_2 \langle x^\mu x^\nu \rangle \langle x_\mu x_\nu \rangle + L_3 \langle x^\mu x_\mu x^\nu x_\nu \rangle \end{aligned}$$

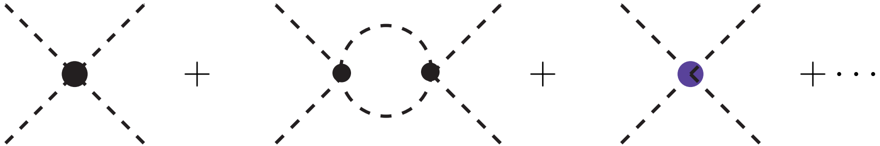
Unitarity of GBS amplitudes

- Consider $\pi^a\pi^b \to \pi^c\pi^d$ scattering amplitude in SU(4)/Sp(4). Expand in Sp(4) channels $\mathbf{5}\otimes\mathbf{5} = \mathbf{1}\oplus\mathbf{10}\oplus\mathbf{14} \equiv \mathbf{A}\oplus\mathbf{B}\oplus\mathbf{C}$ and partial waves, J
- Focus on A $J=0$ channel for this talk
- In this basis, elastic unitarity condition read

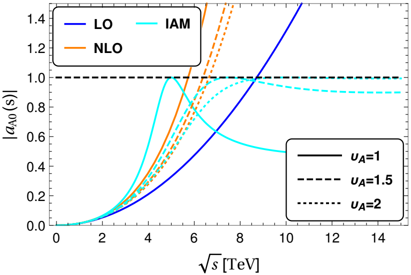
$$\mathrm{Im}\, a_J(s) = |a_J(s)|^2$$

$$\mathrm{Im}\, a_J^{(1)}(s) = |a_J^{(0)}(s)|^2$$

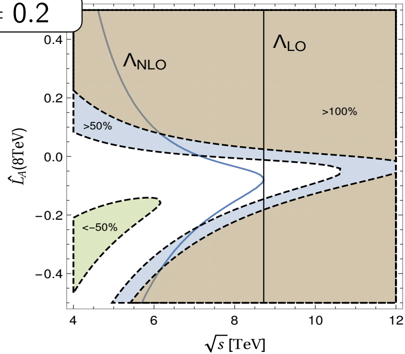
$$\begin{aligned}
a_{A0}(s) &= a_{A0}^{(0)}(s) + a_{A0}^{(1)}(s) + \cdots \\
a_{A0}^{(0)}(s) &= \frac{s}{16\pi f^2} \\
a_{A0}^{(1)}(s) &= \frac{s^2}{32\pi f^4}\left[\frac{1}{16\pi^2}\left(\frac{29}{12} + \frac{46}{18}\log\left(\frac{s}{\mu^2}\right) + 2\pi i\right) + \frac{2}{3}\widehat{L_A}(\mu)\right]
\end{aligned}$$



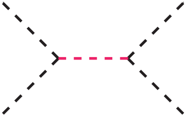
- **Unitarity/Perturbativity test** $|a(s)| < 1$.
- LO prediction is conservative. NLO corrections anticipate unitarity violation.
- Unitarity implies an eventual resonance is lighter than $M_\sigma \lesssim 1.75/\sin\theta$ TeV.
- Lattice results $M_\sigma = 4.7(2.6)/\sin\theta$ TeV (2 Dirac fermions in fundamental of SU(2), Arthur, Drach, Hansen, Hietanen, Pica, Sannino 16')
- Inverse Amplitude Method (IAM) is an Unitarization Model. Guidance for how the full non-perturbative amplitude could look like.



$\sin\theta = 0.2$

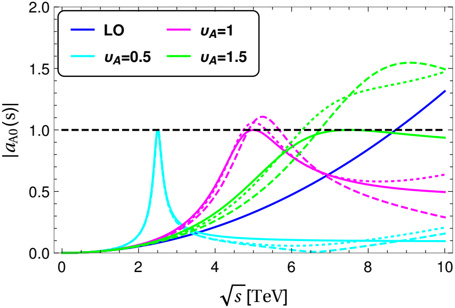


$$\mathcal{L}_\sigma = \frac{1}{2}\kappa(\sigma) f^2 \langle x_\mu x^\mu \rangle + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}M_\sigma^2\sigma^2$$



$$a_{A0}^\sigma(s) = \frac{g_\sigma^2}{32\pi f^2}\left(\frac{5s^2}{m_\sigma^2 - i\Gamma_\sigma m_\sigma - s} - 2m_\sigma^2 + \frac{2m_\sigma^4 \log\left(\frac{s}{m_\sigma^2}+1\right)}{s} + s\right)$$

$$\upsilon_A \equiv \frac{m_\sigma \sin\theta}{\text{TeV}}, \quad \Gamma_\sigma \sim 5\frac{g_\sigma^2 m_\sigma^3}{32\pi f^2}, \quad \kappa(\sigma) = 1 + \kappa'\sigma/f + \kappa''\sigma^2/(2f) + \cdots.$$



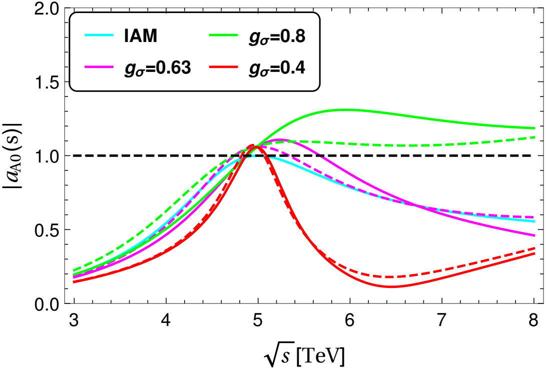
$g_\sigma \equiv \kappa'/2 \sim \sqrt{2/5} \sim 0.63$

Dashed: Fixed width

Dotted: Running width

Solid: IAM

$\sin\theta = 0.2$



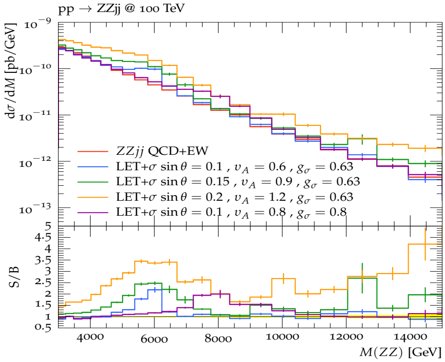
$v = 1$
Solid: Fixed width
Dashed: Running width
$\sin\theta = 0.2$

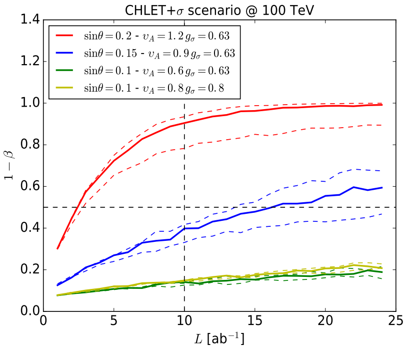
Unitarity and perturbativity give further information about effective Lagrangian beyond pure dimensional analysis:

$$g_\sigma \lesssim 0.8 \text{ and } M_\sigma \lesssim \frac{1.2}{\sin\theta}\text{ TeV}$$

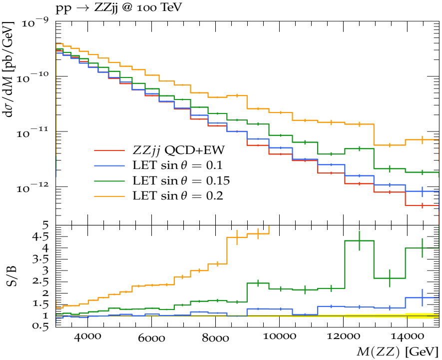
Strong VBS in $pp \to jjZZ \to jj4\ell$

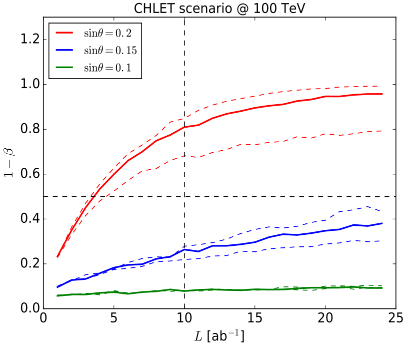
- **Scalar σ resonance at 100 TeV**
- Models implemented via FeynRules in UFO format and events generated with Sherpa generator.
- Typical VBS kinematical cuts applied.
- Mixing $h - \sigma$ very small $\alpha \sim \frac{2m_h^2}{m_\sigma^2}$, suppressed gluon fusion.



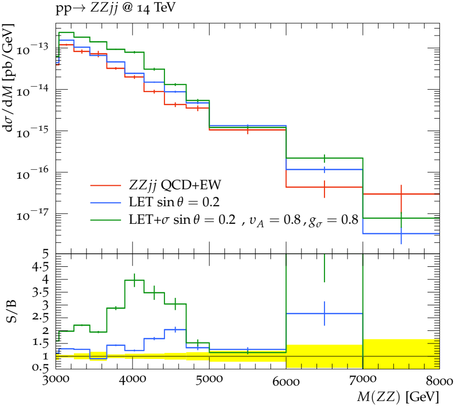


LET no-resonant enhancement at 100 TeV: Conservative scenario, unitarity violation highy suppressed for $\sin\theta < 0.2$





σ resonance at the LHC



- $\sigma \sim 2.9 \times 10^{-4}$ ab very small.
- Other VBS channels imperative for this search.
- Gluon fusion contribution could help.

Conclusion

- Perturbative unitarity gives valuable information about spectrum and couplings of composite sector in CH models. Beyond simple dimensional analysis.
- Scalar sector: σ resonance, $g_\sigma \lesssim 0.8$ and $M_\sigma \lesssim 1.2/\sin\theta$ TeV or *continuum* (vector sector not discussed in this talk, but present in the paper).
- A 100 TeV collider is more appropriate to observe strong effects of CH models in VBS,
- but LHC may be able in a very optimistic case, usually not considered. More study necessary.

CCWZ

- Vacuum $\Sigma_0 = \cos\theta \Sigma_B + \sin\theta \Sigma_H$.
- Minimization $\cos\theta_{min} = \frac{2C_m}{y_t' C_t}$, for $y_t' C_t > 2|C_m|$.
- Generators

$$
\begin{aligned}
V^a \cdot \Sigma_0 + \Sigma_0 \cdot V^{a\,T} &= 0\,, & S^a \cdot \Sigma_B + \Sigma_B \cdot S^{a\,T} &= 0\,,\\
Y^a \cdot \Sigma_0 - \Sigma_0 \cdot Y^{a\,T} &= 0\,. & X^a \cdot \Sigma_B - \Sigma_B \cdot X^{a\,T} &= 0\,,
\end{aligned}
$$

$$
U = \exp\left[\frac{i\sqrt{2}}{f}\sum_{a=1}^{5}\pi^a Y^a\right]\,,
$$

$$
\begin{aligned}
\omega_\mu &= U^\dagger D_\mu U,\\
D_\mu &= \partial_\mu - igW_\mu^i S^i - ig' B_\mu S^6,\\
x_\mu &= 2\mathrm{Tr}\left[Y_a \omega_\mu\right] Y^a\ ,\\
s_\mu &= 2\mathrm{Tr}\left[V_a \omega_\mu\right] V^a\ .
\end{aligned}
$$

Hidden Local Symmetry (HLS)

- Enhance the symmetry group $\mathrm{SU}(4)_0 \times \mathrm{SU}(4)_1$, and embed the SM gauge bosons in $SU(4)_0$ and the heavy resonances in $SU(4)_1$. $\mathrm{SU}(4)_i \to \mathrm{Sp}(4)_i$. $\mathrm{Sp}(4)_0 \times \mathrm{Sp}(4)_1 \to \mathrm{Sp}(4)$ by a sigma field K

$$U_0 = \exp\left[\frac{i\sqrt{2}}{f_0}\sum_{a=1}^{5}(\pi_0^a Y^a)\right], \quad U_1 = \exp\left[\frac{i\sqrt{2}}{f_1}\sum_{a=1}^{5}(\pi_1^a Y^a)\right]. \qquad (1)$$

$$\begin{aligned} D_\mu U_0 &= (\partial_\mu - igW_\mu^i S^i - ig' B_\mu S^6)U_0\,, \\ D_\mu U_1 &= (\partial_\mu - i\widetilde{g}\mathcal{V}_\mu^a V^a - i\widetilde{g}\mathcal{A}_\mu^b Y^b)U_1\,. \end{aligned} \qquad (2)$$

$$\begin{aligned} K &= \exp\left[ik^a V^a/f_K\right]\,, \\ D_\mu K &= \partial_\mu K - iv_{0\mu}K + iKv_{1\mu} \end{aligned} \qquad (3)$$

$$\boldsymbol{\mathcal{F}}_\mu = \boldsymbol{\mathcal{V}}_\mu + \boldsymbol{\mathcal{A}}_\mu = \sum_{a=1}^{d_H}\mathcal{V}_\mu^a V_a + \sum_{a=1}^{d_G-d_H}\mathcal{A}_\mu^a Y_a,$$

$$\begin{aligned} \mathcal{L}_v &= -\frac{1}{2\widetilde{g}^2}\,\langle\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu}\rangle + \frac{1}{2}f_0^2\,\langle x_{0\mu}x_0^\mu\rangle + \frac{1}{2}f_1^2\,\langle x_{1\mu}x_1^\mu\rangle \\ &+ \quad r\,f_1^2\,\langle x_{0\mu}Kx_1^\mu K^\dagger\rangle + \frac{1}{2}f_K^2\,\langle D^\mu K\;D_\mu K^\dagger\rangle\,. \end{aligned}$$

GBS amplitudes

- $\pi\pi \to \pi\pi$ scattering amplitudes expanded in partial wave amplitudes

$$\mathcal{A}(s,t) = 32\pi \sum_{J=0}^{\infty} a_J(s)(2J+1)P_J(\cos\theta)$$

- In order to force elasticity (at least below new heavy states appear), decompose amplitude in conserved quantum number
- **Template: SU(4)/Sp(4), FMCHM**, decompose in multiplets of Sp(4) (very good symmetry at high energy)

$$\mathbf{5} \otimes \mathbf{5} = \mathbf{1} \oplus \mathbf{10} \oplus \mathbf{14} \equiv \mathbf{A} \oplus \mathbf{B} \oplus \mathbf{C}$$

Inverse Amplitude Method

- Phenomenological approach to describe the physics beyond unitarity violation, successful in describing lightest mesonic resonances in pion-pion and pion-kaon scattering up to 1.2 GeV

$$a_{IJ}^{IAM}(s) = \frac{a_{IJ}^{(0)}(s)}{1 - \frac{a_{IJ}^{(1)}(s)}{a_{IJ}^{(0)}(s)}}$$

- Use with caution, not a QFT!
- Generate poles interpreted as dynamically generated resonances in each channel, *e.g.*

$$M_A^2 = \frac{2f^2}{\frac{1}{16\pi^2}\left(\frac{29}{12}\right) + \frac{2}{3}\widehat{L_A}(M_A)}, \quad \Gamma_A = \frac{M_A^3}{16\pi f^2}$$

- Normalized mass: $\upsilon_I \equiv \frac{M_I \sin\theta}{\text{TeV}}, \quad I = A, B, C\,.$

$pp \to ZZjj$ analysis

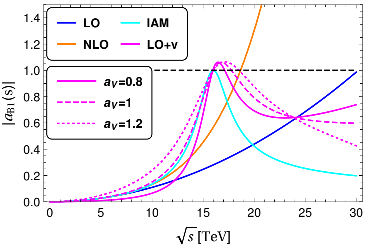
Cuts:

cut	100 TeV	14 TeV
2 jets	$p_T > 30$ GeV , $\|\eta\| > 3.5$, $\eta_1 \cdot \eta_2 < 0$	$p_{T,j} > 30$ GeV , $\|\eta_j\| > 3.$, $\eta_{j_1} \cdot \eta_{j_2} < 0$
ZZ invariant mass	$m_{ZZ} > 3$TeV	$m_{ZZ} > 3$TeV
di-jet invariant mass	$m_{jj} > 1$ TeV	$m_{jj} > 1$ TeV
Zs centrality	$\|\eta_{Z_i}\| < 2.$	$\|\eta_{Z_i}\| < 2.$
Zs momentum	$p_{T,Z_i} > 1$ TeV	$p_{T,Z_i} > 0.5$ TeV

Probability distribution:

$$\mathcal{P}(k;\lambda,\epsilon) = \frac{1}{2\epsilon}\int_{1-\epsilon}^{1+\epsilon} \mathrm{d}x\, e^{-x\lambda}\frac{(x\lambda)^k}{k!}$$

Vector Analysis



$$g_V = -\frac{M_V}{2f} a_V = -\frac{M_V^2(1-r^2)}{\sqrt{2}\tilde{g} f^2} ,$$

$$\mathcal{A}(s,t,u) = -g_V^2 \left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2} + \frac{3s}{M_V^2} \right)$$